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## **Irradiance Calibration of Space-Based Infrared Sensors**

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**July 2004**

**Final Report**

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**20050725 026**

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<b>REPORT DOCUMENTATION PAGE</b>				Form Approved OMB No. 0704-0188	
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<b>1. REPORT DATE (DD-MM-YYYY)</b> 07-2004		<b>2. REPORT TYPE</b> Final Report		<b>3. DATES COVERED (From - To)</b> June 1, 2002 - July 31, 2004	
<b>4. TITLE AND SUBTITLE</b>  Irradiance Calibration of Space-Based Infrared Sensors				<b>5a. CONTRACT NUMBER</b> F19628-98-C-0047	
<b>6. AUTHOR(S)</b>  Russell G. Walker, Sumita Jayaraman, Martin Cohen, and Elizabeth Barker				<b>5b. GRANT NUMBER</b> N/A	
				<b>5c. PROGRAM ELEMENT NUMBER</b> PE 63871 C	
				<b>5d. PROJECT NUMBER</b> PR MSX8	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>  Monterey Institute for Research in Astronomy 200 Eighth Street Marina, CA 93933				<b>5e. TASK NUMBER</b> TA-BS	
				<b>5f. WORK UNIT NUMBER</b> WU-AE	
				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  MIRA-2004-AR05	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Air Force Research Laboratory 29 Randolph Rd Hanscom AFB, MA 01731				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> AFRL-VS-HA-TR-2004-1161	
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b>  Approved for Public Release; Distribution Unlimited					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b>  The purpose of this work is to develop a basis for irradiance calibration of space-based infrared sensors. It is an extension of previous work that fully defines the context of the calibration, and concepts of spectral composites and templates. We discuss the work carried out during the past two years directed toward the production and release of Version 2.0 of the Air Force Bright Spectra Atlas (AFBSA V2.0). This report is also the Explanatory Supplement for the AFBSA V2.0.					
<b>15. SUBJECT TERMS</b> Infrared, Calibration, Stars, Spectra					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>  UL	<b>18. NUMBER OF PAGES</b>  23	<b>19a. NAME OF RESPONSIBLE PERSON</b> 1Lt Tamilyn Becker
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			<b>19b. TELEPHONE NUMBER (include area code)</b> (781) 377-3696

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# 1. INTRODUCTION

Satellites employing infrared sensors are continually being launched by space agencies, such as NASA and ESA and by the US DOD community. The successes of IRAS, ISO, IRTS, MSX, 2MASS, and Spitzer have produced enormous infrared databases. Consequently, there must now be greater emphasis on data verification, validation, and calibration issues to assure that these data sets are of sufficient reliability for application to the quantitative design of advanced space-borne sensors and systems. There is an urgent need not only to rationalize infrared calibration and place it in a common and well-defined context, but also to provide a network of calibrators well distributed across the sky, with a common traceable pedigree. This network should be sufficiently populated to have a member relatively close to any arbitrary direction because satellites and aircraft cannot afford major excursions in pointing to secure measurements of the few traditional calibration objects. Dynamic range, too, is an issue and such a network must include stars both fainter and brighter than today's popular "standards."

The purpose of this work is to develop a basis for irradiance calibration of space-based infrared sensors. It is an extension of previous work (Cohen, et al Papers I-IX, 1992-1998) that fully defines the context of the calibration, and the concepts of spectral composites and templates. Our previous work culminated in the production and release of Version 4 of the Walker-Cohen Atlas of Calibrated Spectra (Annual Report No. 4, July 2002), and the release of Version 1.1 of the Air Force Bright Spectral Atlas (Annual Report No. 3, July 2001). Our approach is based on a self-consistent absolute framework within which radiometry and spectroscopy are unified, with wavelength coverage ideal for calibrating many satellite, airborne, and ground-based sensors.

Our work during the past year has been directed toward the production of Version 2 of the Air Force Bright Spectral Atlas, which will include all of the stars from Version 1.1 plus additional stars that can now be fit with our more sophisticated grid of dusty model stellar atmospheres. The main thrusts here are: inclusion of a larger set of previously rejected stars, expansion of both the photometry and spectral databases to encompass the time variability of the observations, to limit the choice of photometry to those observations done with systems that we can calibrate, and provide a more realistic treatment of spectrum variability. To this end we have pursued three main areas directed toward the production of the AFBSA Version 2.0. The first has been to further develop and expand our photometric databases. The second was to increase our library of infrared spectra by the addition of time-resolved spectra, newly observed spectra, and a more densely populated grid of model spectra of AGB stars. The third was to totally rewrite all of the atlas production code to enable these goals.

This report also serves as the Explanatory Supplement to the AFBSA 2.0.

## 2. AIR FORCE BRIGHT SPECTRAL ATLAS, VERSION 2.0 (AFBSA 2.0)

The AFBSA 2.0 is a set of calibrators selected from the IR-brightest sources in the sky. Our ultimate goal was to create complete (2-35  $\mu\text{m}$ ) spectra for all stars brighter than zero magnitude in the infrared. To do this we utilized spacebased spectra from the IRAS Low Resolution Spectrometer (LRS), the ISO Short Wavelength Spectrometer (SWS), and other groundbased and airborne spectral observations from the past and recent literature, as well as spectra generated by theoretical and/or empirical models. These spectra are then normalized by means

of well-characterized photometry to bring them into the photometric system described by Cohen, et al (Papers I-IX, 1992-1998).

Candidate stars for the AFBSA are selected from the IRAS all-sky survey, the Cal. Tech. Two Micron Sky Survey, and the MSX point source catalog. For inclusion in the catalog, a star must be brighter than zero magnitude in the respective survey bands.

The brighter in the mid-infrared the required calibrators are, the greater the likelihood of encountering abnormal stars such as heavily dust-shrouded, long-period, cool variables. At the present time we lack detailed information on the spectral variations of these stars with the phase of their light curves, even for those objects whose variations are supposedly periodic. Variability of the majority of the IR-bright stars is the foremost problem to be addressed if these objects are to be accepted as reliable calibrators.

As with its predecessors, AFBSA V2.0 is limited in its scope and does not achieve the overall AFBSA goals either in quantity or quality of the sources. It is a result of a further "testing of the waters" beyond that of the AFBSA 1.1 but, nevertheless, serves a number of useful purposes. It alerts the systems designer to the potential bright calibrators that will be available for calibration of spacebased, groundbased, and airborne IR systems. The irradiance levels and dynamic range possible are well-defined, even though many absolute irradiance levels have, at present, unacceptably large uncertainties for radiometric calibration. Many of these will still be useful astrometric calibrators and knowing the range of their irradiances will improve infrared acquisition by enabling discrimination among multiple objects in the field. Further, many stars are identified in this version that do have reliable and non-varying irradiances with acceptable errors, and are immediately applicable for radiometric calibration. Finally, production of this version of the atlas has identified to the authors those stars that can be readily elevated to precise calibration status, and those that will require gargantuan efforts.

AFBSA Version 2.0 includes all of the stars from Version 1.1 augmented by 291 stars that were previously lost due to a lack of photometry, 48 stars that were previously lost due to the poor quality of the LRS, and 99 new stars that can now be templated. Thus the total number of stars in the AFBSA 2.0 is 1835.

### 3. PHOTOMETRY DATABASE

The irradiance levels of the spectra presented in AFBSA Versions 1.0 and 1.1 were determined by normalization of the IRAS Low Resolution Spectra (LRS) to the IRAS 12  $\mu$ m inband irradiance. Spectra thus produced were subject to the full uncertainty of the IRAS 12  $\mu$ m photometry, typically 6 to 9 percent. Photometry at other wavelengths was used only as a guide to the reasonableness of the final spectrum. This additional photometry was calibrated by a zero-order method that estimated spectral irradiance at the authors' reported effective wavelengths for their bandpass filters. In Version 2.0 we normalize the spectra to all the "well characterized photometry" that is available for the star, using a technique similar to that used to produce the Walker-Cohen Atlas (WC). That is, we will use all the photometry where the spectral response of the system is known, its zero-point can be established on our expansion of the common system defined by Cohen, et al. (1992), and the measurements are complete with uncertainties reported. Furthermore, in Version 2.0 we desire to make a more definitive treatment of the variability of the stellar spectrum than was done in Versions 1.0 and 1.1. To do this we required

the dates of the observations. Therefore, we have compiled a new expanded photometry database from the available literature. Table 1 lists the sources of photometry in the current database used for production of AFBSA V2.0.

Table 1. AFBSA V2 Photometry Database			
Catalog	No. of stars	No. of Observations	Wavebands
IRAS	1435	5287	12, 25, 60 $\mu\text{m}$
MSX	685	7817	A, B1, B2, C, D, E
SAAO	124	3553	JHKL
DIRBE	207 light curves	> 20000	JHKL, 12, 25 $\mu\text{m}$
Foque	516	516	JHKLM
Valinhos	584	584	JHKLM
CIO-5	1693	32852	JHKLMN

Our IRAS database is a subset of the IRAS WSDB (see Beichman, et al, 1988) containing time-tagged fluxes and uncertainties for the 12 $\mu\text{m}$ , 25 $\mu\text{m}$ , and 60 $\mu\text{m}$  bands. The MSX database was extracted from the MSX PSC (Egan, et al, 1999). The DIRBE database is from Table 5 in Smith, 2003. The mean, maximum, and minimum DIRBE fluxes were used when available. The SAAO, Valinhos, and Foque datasets were contained within our new CIO-5 (Gezari, et al, 1999) database.

We returned to the original data references for the CIO-5, verifying and re-entering the original data from those references that had the greatest number of observations of the most stars. We were able to calibrate the data in only a fraction of the references (based on the availability of calibration information within the references). In our previous CIO-5 database, some data taken at the same wavelength for individual stars had been averaged together. For the current database, we re-entered the original data, including the date of observation when available. This version also includes the author's estimates of measurement errors. When not provided by the original reference, we have assumed a date of observation as the month and year of the published article. When a reference included data from multiple observatories, we noted each observatory with each observation, in order to select the proper calibration for the system (filter, detector, atmosphere) used.

We also searched the General Catalog of Variable Stars (<http://heasarc.gsfc.nasa.gov/W3Browse/all/gcvs.html>) for all of our CIO-5 stars on 5 May 04 to find any new periods and epochs of maximum light for each star in the CIO-5 catalog. If a star is a known variable, but the period is undetermined, we have listed the period in the data file as -99. A period of 0 denotes a nonvariable star or one with no information at all. If an epoch of maximum light is known, it is given in Julian Days (JD), otherwise it is 0.

In order to distinguish between high quality data and lower quality photometry data, we have developed a "quality characterization," which consists of a six-character string of zeros and ones, with position within the string indicating separate characteristics. Each character of the string can be either 0 or 1, with 0 indicating a poor quality and 1 indicating a good quality. The



position of each character represents the quality of the data, as follows (in order): photometric uncertainty, calibrated passband, calibrated zero point offset, date of observation, period, and epoch of maximum light. Thus, each line of data is given a characterization based on the qualities of that data, i.e. '011001.'

The date of observation has a separate quality flag (immediately following the date of the observation in the data file), a single digit integer, ranging between 0 and 3. Each value indicates a particular precision for the tabulated date, as follows: 3 = date given in original reference, 2 = dates of observing run given by reference (usually a few days in length), 1 = month and year of observation given by reference, 0 = month and year of publication assumed as observation date, since no other dates were provided by reference.

To be considered "fully characterized" each piece of photometry was required to have the following: a) the observed flux or magnitude, b) the uncertainty in the flux or magnitude, c) the normalized spectral response function of the combined filter/detector/atmospheric transmission, d) the zero point of the photometry, and e) the time of observation. Zero points are most often determined from observations of WC standards. We would like to use only "fully characterized" photometry, however, in the real world we must use photometry that is less than ideal. We defined three photometric categories: fully characterized, partly characterized, and poorly characterized. These designations are retained as flags attached to the photometry in the spectrum headers, and reflect the weights given to the photometry when used to normalize the spectra. An inverse variance weighted least squares technique is used to normalize the spectrum to the photometry. These additional weights are multipliers to the standard weights. The definitions and actions for each category are as follows:

- a) Fully Characterized – This is as explained above and carries a weight of unity.
- b) Partly Characterized – In this case we are required to supply one piece of missing data, for example, we may not have the spectral response and have to adopt a generic curve, such as we did for the IRC 2.2  $\mu\text{m}$  data. This photometry would carry a weight of 0.75. If an item was missing we did the following: b1) Flux or magnitude uncertainty is missing – supply 5 percent for wavelengths short of 5.0  $\mu\text{m}$ , 10 percent for longer wavelengths; b2) The filter spectral response is missing – supply a generic filter response and increase the uncertainty by 5 percent (in the rss sense); b3) The zero point is missing or cannot be obtained from WC standards – supply a zero point of 0.0 magnitudes and increase the uncertainty by 5 percent (in the algebraic sense); b4) The time of observation cannot be determined – no action was taken since we abandoned trying to group observations by the phase of the light curve.
- c) Poorly Characterized - In this case two or more items were missing – we treated them as in the above Partly Characterized case, increasing the uncertainties for each item missed (combining the algebraic ones first, then rss with the filter 5 percent if appropriate). The weight for this photometry is  $(4-n)/4$  where n is the number of missing items.

University of Minnesota (CIO-5 reference # 800213) observations were scanned, checked, error corrected, reformatted and then included in our new CIO-5 data file. Also digitized was the South African Astronomical Observatory (SAAO) data, checked and corrected for errors.

Our CIO-5 data file has 12 columns, as follows (in order): IRAS name of star, wavelength of observation ( $\mu\text{m}$ ), photometry, uncertainty of photometry, code indicating units of photometry, observation epoch (JD), quality code of date of observation epoch, period (days), epoch of maximum light (JD), original CIO-5 reference number, alternate star name, data quality characterization, observatory/system name.

## 4. SPECTRAL DATABASE

### 4.1 The IRAS Low Resolution Spectrometer (LRS) Database

The LRS spectra in previous versions of the AFBSA used the standard time-averaged spectra produced by the LRS extraction program. The original complete set of time-resolved spectra were extracted for the AFBSA V2.0. The data were of the form `a0n_StarRaDec.spe1` where `n` ranges from 2 to 15, with `n-1` being the number of spectra observed for that star. The `a01*` files represent time averaged-spectra and were not directly used at all. The data was reduced from the raw, uncalibrated and uncorrected data to the final complete spectra using the following procedure:

**4.1.1 Finding the IRAS 12 micron flux:** The time-tagged IRAS working survey database (WSDB) was used to determine the value of the 12 micron flux at a given time. The 12 micron flux is a pre-requisite for normalizing the spectra. There were three challenges in this regard. For some observations there were no corresponding WSDB fluxes found and the values were interpolated using a simple bi-linear interpolation in the temporal domain. For other observations, there were multiple values in the WSDB database and it was necessary to examine the detailed log files that were used to create the raw LRS spectra to associate the fluxes with the correct spectra. The final correction that needed to be taken into account was the difference in the star name between the WSDB and LRS data sets. The LRS RA and Dec coordinates could be off by as much as 1 or 2 arcminutes leading to a different LRS name for a list of spectra for the same star. For example, a star with the IRAS PSC2 name 0001+4826 will have 0001p4825 in the original LRS database. The WSDB was taken as the basis to search for the LRS spectra and the final spectra names were corrected to agree with the WSDB names. An intermediate log file was created which listed the WSDB name, time of observation, 12 micron flux and the corresponding LRS raw data file.

**4.1.2** The log file was used as input for a FORTRAN code that also read in the raw data and created a calibrated spectrum between 7 and 22 microns that was normalized to the 12 micron IRAS WSDB flux. Incomplete spectra were removed from the data. The analysis was done for the 685 stars observed by MSX, as well as the 1638 observed by IRAS which resulted in slightly over 7000 spectra for the 1914 stars in the AFBSA V2.0 time-resolved LRS catalog.

The IRAS LRS spectra span the wavelength range from 7.67  $\mu\text{m}$  to 22.37  $\mu\text{m}$ . Since our goal is to produce a spectral catalog spanning the range 2  $\mu\text{m}$  to 35  $\mu\text{m}$ , we must extend the LRS spectra at both short and long wavelengths. This is accomplished by photometric normalization of 1) composite spectra from the Walker-Cohen Atlas, Release 4 for nonvariable stars, 2) ISO SWS spectra where available for variable stars, and 3) by splicing the IRAS LRS to spectra produced from models of the dust enshrouded AGB stars.

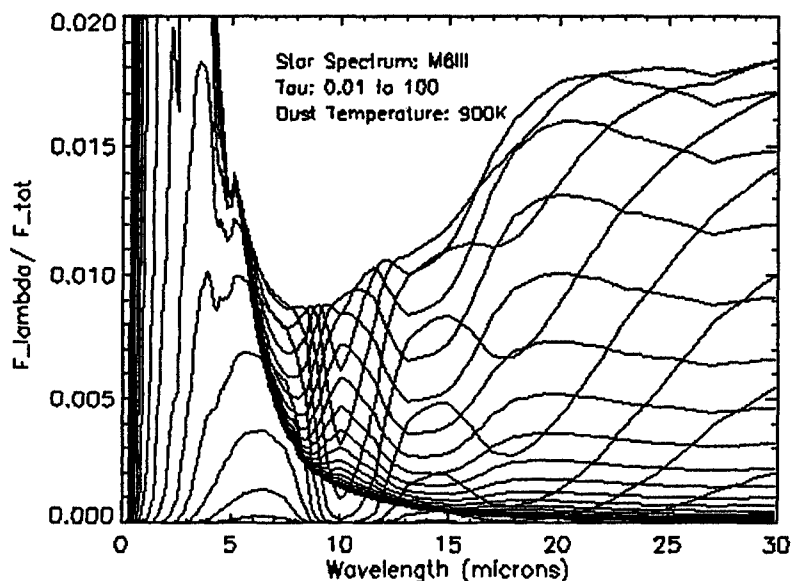
### 4.2 The Model Spectral Database

In AFBSA Versions 1.0 and 1.1 the spectra were constructed from the LRS (for the mid-wavelengths) with the best-fitting spectra selected from the library of 87 SKY 4 categories (Cohen, et al., 1993) to extrapolate to longer and shorter wavelengths. During this process we noted that the grid of available spectra poorly fit many stars, and we concluded that a more extensive set of model spectra was in order.

We have adopted the DUSTY code (Ivezic, et al., 1999) since about 94 percent of the stars in the AFBSA V1.1 are Asymptotic Giant Branch (AGB) stars. DUSTY allows a wide

range of input parameters to customize the models. We have computed two sets of grids, one for the oxygen-rich stars (AGBMs) and one for the carbon-rich stars (AGBCs). We have explored the range of model dust shell parameters, such as chemical composition, relative abundances, grain size distribution, dust density distribution, temperature at the inner dust shell boundary, and optical depth of the dust. The objective was to find those sets of parameters that produce spectra and colors that represent the AGB stars in our list.

Figure 1 shows one set of models for an oxygen-rich star. The grain size distribution is that given by Kim, Martin, and Hendry (1994) with the coefficients derived by Jura (1994) to well represent the dust distribution in IRC 10216. The temperature of the inner radius of the shell is 900K, and the density in the shell falls as  $1/\text{distance}^2$  from the star as in the case of a steady state wind with constant velocity.

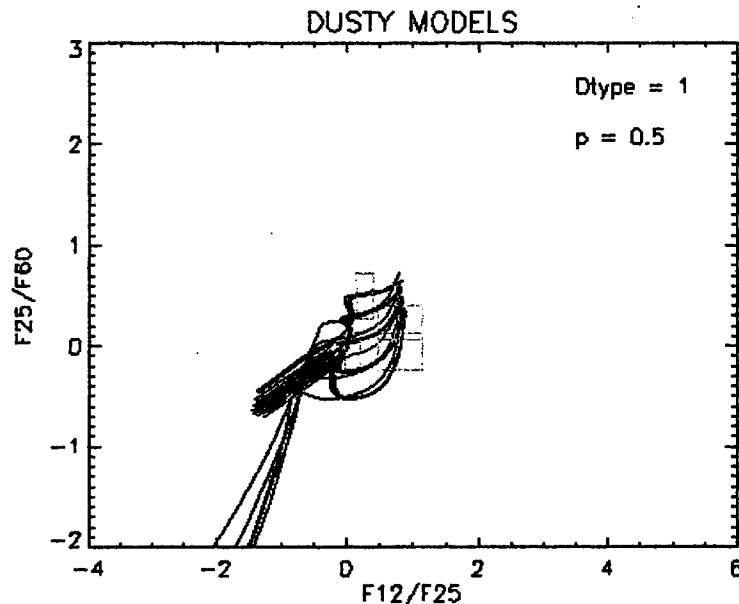


**Figure 1. A Sample of the DUSTY Models Computed for Oxygen-rich AGB Stars. The flux given on the ordinate is the spectral flux  $F_\lambda$  normalized by the total flux from the star.**

The grain composition is that of warm astronomical silicates as given by Ossenkopff et al. (1992). The 10 and 20 $\mu$ m silicate features are easily seen, with the 10 $\mu$ m feature reversing from prominent emission to deep absorption as the optical depth is increased. It is clear in the figure that, except at very small optical depths in the dust, the details of the input stellar spectrum are quickly lost and contribute little to the shape of the emergent dust spectrum.

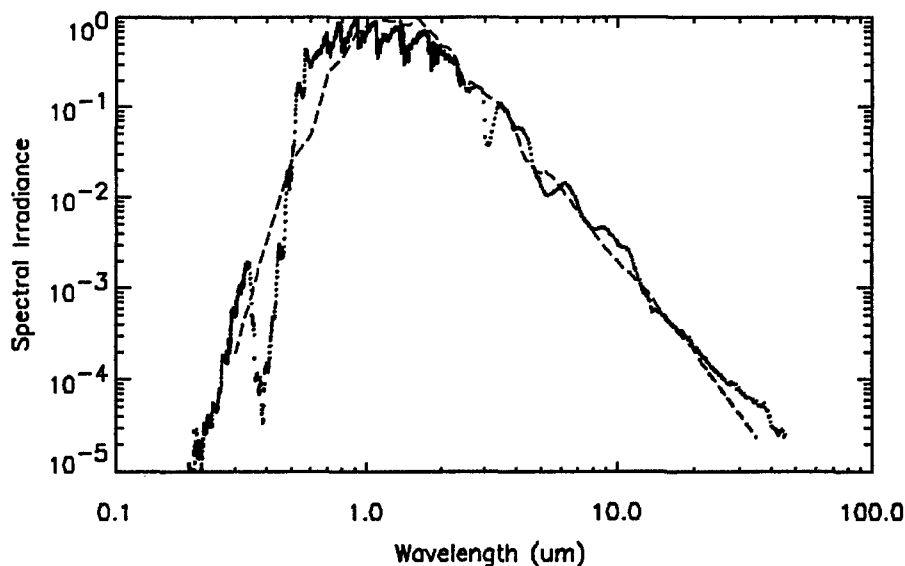
The production of AFBSA V2.0 uses DUSTY model spectra selected from a sub-sample of the total DUSTY grid by their positions in the IRAS F12/F25, F25/F60 “color-color” plane, with F12, F25, and F60 being the irradiance in the IRAS passbands centered at 12, 25, and 60 $\mu$ m. We therefore require that, although our final spectra extend out to only 35  $\mu$ m, the chosen DUSTY spectrum will be in agreement with the in-band fluxes observed by IRAS at 12, 25, and 60 $\mu$ m. Figure 2 is an example of how some DUSTY model IRAS colors extend through the region in the color-color plane. The boxes are the stellar occupation zones for AGB stars defined by Walker and Cohen (1988). It is clear that the requirement to reproduce the IRAS colors greatly constrains the range of applicable DUSTY spectra. Within these constraints we have adopted the set of models defined by the parameters in Table 2. The dust composition is

specified by choosing the fraction of SiO (warm or cold) from Ossenkopff et al. (1992), Amorphous Carbon (amC) from Hanner (1988) and silicon carbide (SiC) from Pegourie (1988). The selections for each model are also listed in the table. Each run of the code generates a number of models distributed evenly within a given logarithmic range of the optical depth. All our sets used the optical depth range of 0.001 to 100 with 30 models in this range. The grain size distribution  $n(a)$  within the disk is chosen to be the KMH (Kim, Martin and Henry, 1994) distribution with an exponential falloff:  $n(a) \propto a^{-q} e^{(-a/a_0)}$  where  $q = 3.5$ ,  $a(\text{min}) = 0.005$  microns and  $a_0 = 0.2$  microns. The spherical density dust distribution is an analytical one falling off as  $1/\text{distance}^2$  from the central star. The dust shell extends to 1000 times its inner radius. The parameters  $Dtype$  and  $p$  define the density distribution.



**Figure 2. IRAS Flux Ratios (expressed as magnitudes) of Some DUSTY Models Superimposed on a Plot of the Stellar Occupation zones of Walker and Cohen (1988) for AGB stars.**

Figure 3 shows the spectra adopted for the central stars of the DUSTY models. The carbon star spectrum is the result of splicing together: the SWS spectrum of R Scl (2.3 to 45  $\mu\text{m}$ ), the Lancon-Wood (2000) spectrum of T Cae (0.5 to 2.5  $\mu\text{m}$ ), a ground-based spectrum from Gunn and Stryker, (1983) of AW Cyg (0.32 to 1.06  $\mu\text{m}$ ), and IUE spectra of AW Cyg (.17 to .33  $\mu\text{m}$ ). The M6III spectrum was spliced from our sky model library spectrum for G Her (2 to 35  $\mu\text{m}$ ), an unpublished compilation (0.3 to 1.08  $\mu\text{m}$ ) by one of us (MC), and a blackbody interpolation from 1.08 to 2.0  $\mu\text{m}$ .



**Figure 3. Spectra Used for the Central Stars in the DUSTY Code. The dotted curve is the spectrum of the carbon star, while the dashed curve is that of the M6III star.**

**Table 2. Parameters of the Final Set of DUSTY Models Used in the AFBSA V2.**

Central Star (Total)	Optical Depth, $\tau$ at 2.2 $\mu$ m	No. of $\tau$ 's per model	Dust Temperature (K) at the inner shell boundary	Fractional Composition			Dtype	p
				SiO	AmC	SiC		
C-Star (600 models)	0.001 to 100	30 log. Steps	300, 500, 700, 900, 1100	0.0	1.0	0.0	1	0.5, 2
				0.0	0.9	0.1	1	0.5, 2
				0.0	0.8	0.2	1	0.5, 2
				0.0	0.7	0.3	1	0.5, 2
M6III (150 models)	0.001 to 100	30 log. Steps	300, 500, 700, 900, 1100	1.0	0.0	0.0	1	0.5, 2

### 4.3 The ISO Short Wavelength Spectrometer (SWS) Database

During the production of the AFBSA V1.0 and V1.1, visual inspection of the spectral fits rejected 316 stars due to the poor quality of the LRS spectra. The ISO SWS database of 1248 spectra has recently become available to the general public and we decided to replace the LRS spectra of the rejected stars with SWS spectra. We downloaded the SWS from their website and associated the SWS positions with those of our input list of 1914 stars. We found 343 SWS spectra of our objects, with 48 among the 316 stars with rejected LRS spectra. At this point we

decided to use the SWS for as many of the AFBSA stars as possible, and not just to replace those from the LRS spectra reject list. We excluded those stars that could be represented by spectral composites or templates (Cohen, et al Papers I-IX, 1992-1998).

The 343 SWS spectra were first converted from flux density (Jy) to spectral irradiance ( $\text{W}/\text{cm}^2/\mu\text{m}$ ), then smoothed (using a 101 point boxcar average) to a resolution comparable to the LRS spectra and the DUSTY model spectra. The smoothed spectra were then sampled at the wavelengths of the DUSTY model spectra (see section 3.1). The smoothing and sampling code displayed the spectra to enable a visual comparison at each stage of the process. It also allowed the operator to reject SWS spectra that failed to pass his qualitative assessment of goodness. Forty-six SWS spectra were thus rejected, due to incomplete spectral coverage, spectral discontinuities, or excess noise. Our final SWS database consists of 297 spectra, each sampled at 158 wavelengths from 2.4  $\mu\text{m}$  to 35.0  $\mu\text{m}$ , for 212 AFBSA stars.

#### 4.4 The Template and Composite Spectral Database

**Table 3. Calibrated Spectra of Stars Brighter Than Zero Magnitude**

MODELS		COMPOSITES		TEMPLATES	
STAR	FILE	STAR	FILE	STAR	FILE
(IRAS Name)		(IRAS Name)		(IRAS Name)	
06429-1639	acma0791.cmp	01069+3521	band1093.cmp	00121-1912	HD1038.tem
18352+3844	alyr0791.cmp	02596+0353	acet0396.cmp	00238-4234	HD2261.tem
		04330+1624	atau0392.cmp	00254-3317	HD2429.tem
		07422+2808	bgem0994.cmp	00376+5615	HD3712.tem
		08214-5920	ecar1295.cmp <sup>3</sup>	00410-1815	HD4128.tem
		09251-0826	ahya1294.cmp	00439+1512	HD4408.tem
		10193+4145	uuma0496.cmp	01261-4334	HD9053.tem
		12283-5650	gcru0396.cmp <sup>4</sup>	01516-4632	HD11695.tem
		14133+1925	aboo0997.cmp	02008+4205	HD12533.tem
		16433-6856	atra1295.cmp <sup>5</sup>	02043+2313	HD12929.tem
		17554+5129	gdra1295.cmp	03019+3838	HD19058.tem
		23013+2748	bpeg0392.cmp	03479-7423	HD24512.tem
TEMPLATES		TEMPLATES		TEMPLATES	
STAR	FILE	STAR	FILE	STAR	FILE
(IRAS Name)		(IRAS Name)		(IRAS Name)	
04001-6217	HD25705.tem	10172+2005	HD89484.tem	15011-2505	HD133216.tem
04537+3305	HD31398.tem	11006+6201	HD95689.tem	15186-3604	HD136422.tem
04589+4100	HD32068.tem	11284+6936	HD100029.tem	16117-0334	HD146051.tem
05033-2226	HD32887.tem	11358+0824	HD101153.tem	16127-7834	HD145366.tem
05146+4244	HD34269.tem	11432+0648	HD102212.tem	16164+5952	HD147232.tem
05562+4556	HD40239.tem	11462-2628	HD102620.tem	16433-6856	HD150798.tem
06133+6132	HD42973.tem	12148-6741	HD106849.tem	16469-3412	HD151680.tem
06199+2232	HD44478.tem	12517-0915	HD112142.tem	16501-4258	HD152161.tem
07276-4311	HD59717.tem	12530+0340	HD112300.tem	17133+3651	HD156283.tem
08214-5920	HD71129.tem	13495+3441	HD120933.tem	17403-3238	HD160840.tem
09180+3436	HD80493.tem	14037-3607	HD123139.tem	18142-3646	HD167618.tem
09297-5648	HD82668.tem	14427+2717	HD129989.tem	18177-2951	HD168454.tem
10154-6104	HD89388.tem	14508+7421	HD131873.tem	18399-1920	HD172816.tem
19286+2751	HD183913.tem	20442+3347	HD197989.tem	22469-1351	HD216032.tem
19438+1029	HD186791.tem	20451-0512	HD198026.tem	23070+0824	HD218634.tem
19451+1824	HD187076.tem	22150-6030	HD211416.tem	23551+2451	HD224427.tem
19565+1921	HD189319.tem	22274+4726	HD213310.tem	23594-0617	HD224935.tem
19595-2751	HD189763.tem	22296-6214	HD213442.tem		

Notes to Table 3:

1. All of the above spectra are part of Release 4.0 of the Air Force Calibration Atlas that can be obtained in its totality directly from Dr. Steve Price, Air Force Research Laboratory, L. G. Hanscom Air Force Base, MA. 01731, Email: Steve.Price@hanscom.af.mil.
2. These ASCII files are in different formats than the AFBSC V2 spectrum files. Information pertaining to the construction of the calibrated spectra is contained in the header as is explanatory data for the format and content of the tabulated quantities.
3. The spectrum (ecar1295.cmp) is incomplete, covers 2.9  $\mu\text{m}$  to 35.0  $\mu\text{m}$ . For complete coverage use the template spectrum HD71129.tem.
4. The spectrum (gcru0396.cmp) is incomplete, covers 3.95  $\mu\text{m}$  to 35.0  $\mu\text{m}$ .
5. The spectrum (atra1295.cmp) is incomplete, covers 2.9  $\mu\text{m}$  to 35.0  $\mu\text{m}$ . For complete spectral coverage use the template spectrum HD150798.tem

The 79 spectra in Table 3 will provide the most accurate and reliable calibration of bright stars in the infrared. These are all normal stars with irradiance variability that is less than a few percent, in contrast to the large amplitudes that are seen in most of the other stars in the AFBSA V2. An additional 45 bright stars have been found that also have small or no variability. The spectra of these objects have been estimated by normalization of composites of the same spectral type to well characterized photometry in the same way that the \*.tem spectra were derived. They too will provide accurate and reliable calibrations. These stars are listed in Table 4. We strongly recommend that calibrators be chosen from among the 124 stars of Tables 3 and 4 whenever possible.

**Table 4. Additional Template Calibration Spectra**

FILENAME	FILENAME	FILENAME	FILENAME
00254-1156.AFBSA2	08461-2827.AFBSA2	14248-5927.AFBSA2	18585-3701.AFBSA2
00254+1736.AFBSA2	08555+1102.AFBSA2	14280-2952.AFBSA2	19194+1734.AFBSA2
02036-1027.AFBSA2	09203-5220.AFBSA2	14455-3625.AFBSA2	19577+1722.AFBSA2
02339+3402.AFBSA2	10456-5712.AFBSA2	15576-5400.AFBSA2	20241+3811.AFBSA2
02455-1240.AFBSA2	10562-6235.AFBSA2	17215-7114.AFBSA2	20322+4215.AFBSA2
03449+6522.AFBSA2	11011-6651.AFBSA2	17297+1747.AFBSA2	21402+4532.AFBSA2
04382-1946.AFBSA2	11113-5949.AFBSA2	17360-3140.AFBSA2	22366+5632.AFBSA2
04497+1410.AFBSA2	11179-6458.AFBSA2	17393-3004.AFBSA2	23142-0759.AFBSA2
06067+3125.AFBSA2	11251+4527.AFBSA2	17468-2900.AFBSA2	23278+6000.AFBSA2
06118+2231.AFBSA2	11485-1055.AFBSA2	17593-2328.AFBSA2	
07104+1614.AFBSA2	12106-3350.AFBSA2	18359+0847.AFBSA2	
07207+8230.AFBSA2	14059+4405.AFBSA2	18527+3650.AFBSA2	



## 5. THE AIR FORCE BRIGHT SPECTRAL ATLAS VERSION 2.0 (AFBSA V2.0) PRODUCTION CODE

As previously noted, variability of the shape and amplitude of the star's spectrum is a major consideration for the bulk of the AFBSA stars. It was our goal to improve our treatment of variability over that done for the AFBSA 1.0 and 1.1. The ideal situation would be to have the ability to "dial-a-spectrum" for each phase of the stellar light curve. This proves to be beyond our present technical capability. We have been forced to compromise, and instead we chose to present: (1) a mean spectrum that best fits all the available well-characterized photometry, regardless of the phase of the light curve, (2) an upper envelope spectrum such that the amplitude of 95 percent of the available photometric observations fall below it, and (3) a lower envelope spectrum that lies below the amplitude of 95 percent of the same photometric observations. Each spectrum is complete with photometric error estimates.

All of the production code of the AFBSA 2.0 was done in the RSI Interactive Data Language (IDL). Three input star lists were used, the template/composite list, the SWS list, and the LRS/DUSTY list. Separate run streams were selected appropriate to each list, however, each run stream used the same base computational modules. The flow of the procedure was as follows: (1) Read into memory all the photometry databases, (2) Select a star from one of the three lists, (3) Find its spectral shape (template/composite, SWS, or LRS), and :

(a) If a template/composite, then there is no stellar variability and the composite for the spectral type of the star is the mean spectral shape to be normalized by the photometry.

(b) If the star has a SWS spectrum and only a single spectrum is found, use this spectral shape for fitting all three (upper envelope, mean, and lower envelope). If two or more spectra are found, calculate the mean shape from the median of all the spectral shapes found. Calculate the integrated energy ( $\int \lambda F_{\lambda} d\lambda$ ) for each shape, use the one with largest energy as the upper envelope spectral shape, and the one with the smallest integrated energy as the lower envelope spectral shape.

(c) If the star has an LRS spectrum and only a single LRS is found, extend both the short and long wavelength portions of the spectrum by splicing the DUSTY model spectrum defined by its colors in the IRAS WSDB ( $F_{12}/F_{25}$ ), ( $F_{25}/F_{60}$ ) color-color plane. Use the resulting shape for fitting all three (upper envelope, mean, and lower envelope). If two or more LRS spectra are found, extend the LRS spectra by splicing each to its appropriate DUSTY model spectrum defined by its colors in the IRAS WSDB ( $F_{12}/F_{25}$ ), ( $F_{25}/F_{60}$ ) color-color plane. Calculate the mean shape from the median of all the extended LRS found. Calculate the integrated energy ( $\int \lambda F_{\lambda} d\lambda$ ) for each shape; use the extended LRS with largest integrated energy as the upper envelope spectral shape, and the one with the smallest integrated energy as the lower envelope spectral shape.

(4) Extract all the photometric observations of the star that reside in our databases:

(a) Convert the observed photometric quantity (magnitude, Jansky,  $\text{w}/\text{cm}^2/\mu\text{m}$ , etc) to inband flux ( $\text{w}/\text{cm}^2$ ) and  $1\sigma$  inband flux error ( $\text{w}/\text{cm}^2$ ) for each photometric wavelength band.

(b) Using the mean spectral shape calculate the inband flux for each photometric wavelength band, and the auxiliary quantities, the isophotal flux, isophotal wavelength, and spectral bandwidth.

(c) Compute the ratio of the observed inband flux to the calculated inband flux ( $R_{\lambda} = F_{\lambda\text{obs}}/F_{\lambda\text{calc}}$ ) and the  $1\sigma_R$  variance in the ratio for each wavelength ( $\lambda$ ) band.

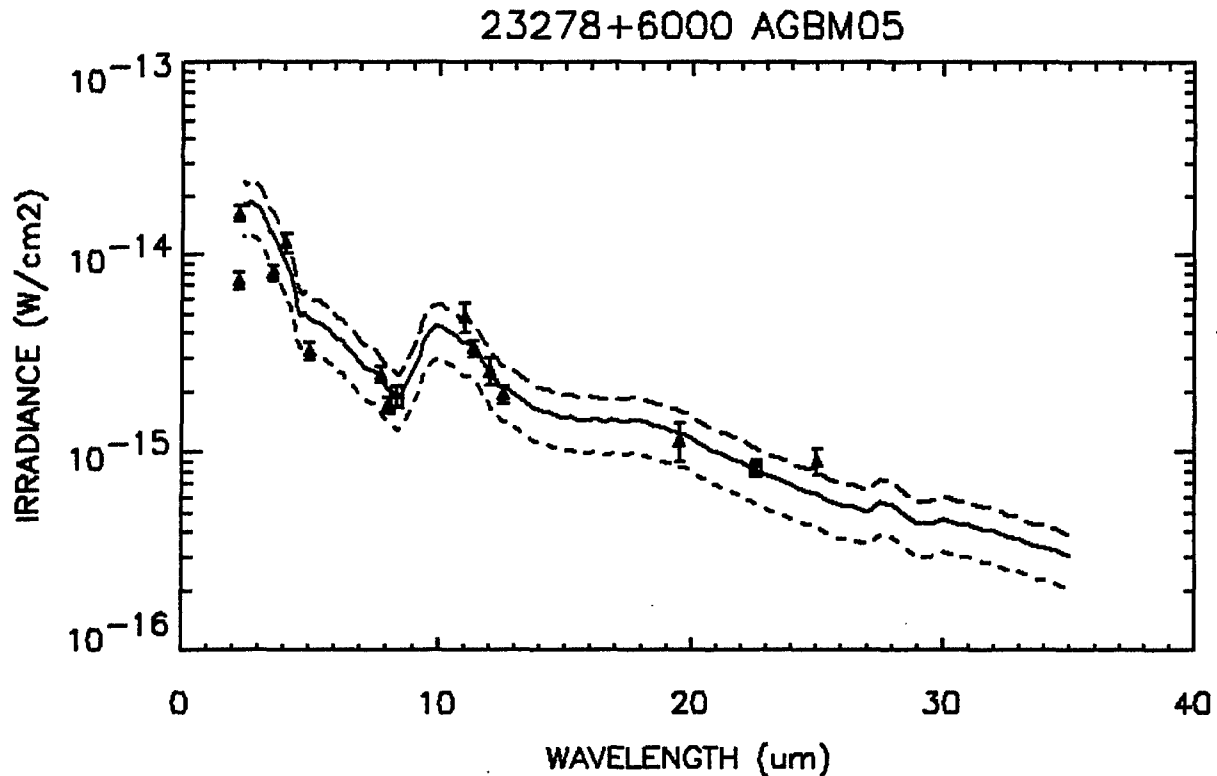
- (d) Calculate the inverse variance weighted mean ratio,  $R$ , and its standard deviation. Normalize the mean spectrum by  $R$  to find the spectral irradiance ( $\text{W}/\text{cm}^2/\mu\text{m}$ ) and its error at each wavelength sampled.
- (e) Repeat steps (b) through (c) for both the upper and lower envelop spectra.
- (f) Sort the ratios derived in (e) and use the 95 percent points to normalize the upper and lower envelop spectra and their errors.
- (g) Write the spectrum and header information to the output spectrum file.

## 6. THE SPECTRAL ATLAS

The AFBSA Version 2 consists of 1835 ASCII files, one for each cataloged star, the assembled databases, software code for accessing the data, plus this Explanatory Supplement, all delivered via CD-ROM. The information is contained in five sub-directories; \Databases, \Software, \Documentation, \Spectra, and \Standards. The files in \Spectra are written in the format discussed in the following paragraphs, while those in \Standards are in the formats in which they were originally published with the exception of those spectral files with extension \*.AFBSA2. These spectra were newly "templated" as part of the production of AFBSA Version 2, and have the same format as those in the \Spectra directory. The names of the spectrum files in the \Spectra subdirectory were constructed from the star's IRAS name plus an extension consisting of AFBSA and its Version number. For example: 00254-1156.AFBSA2; 00254-1156 is the IRAS name, and AFBSA2 labels this as a spectrum file of AFBSA Version 2.

An AFBSA Version 2 spectrum file consists of an extensive header identifying the star and the spectrum chosen to represent it, information relating to the production of the spectrum, and the basis for its variability status. Included is a list of all the photometry found for that star in our database with our conversion to isophotal flux at the tabulated isophotal wavelength. The bulk of the information is self explanatory; however, the CIO photometry section also includes three additional columns headed Code, Reference, and Star Names. The Code defines the quantity tabulated in the Magnitude column (see CIO Addition 5 for a complete listing). The Reference column contains a number identifying the original source of the data. The CIO Addition 5 gives the complete list of reference papers. The final column lists some additional names for the star in question.

Following the header the derived spectral data are tabulated in five columns. The first column is the wavelength ( $\mu\text{m}$ ), the second is the spectral irradiance ( $\text{W cm}^{-2} \mu\text{m}^{-1}$ ) of the mean spectrum, and the third is the uncertainty ( $1\sigma$ ) in the spectral irradiance of the mean spectrum expressed as a percentage of the irradiance. The fourth column is the lower envelop spectral irradiance ( $\text{W cm}^{-2} \mu\text{m}^{-1}$ ) which lies below 95 percent of the observed photometry, and the fifth column is the upper envelop spectral irradiance ( $\text{W cm}^{-2} \mu\text{m}^{-1}$ ) which lies above 95 percent of the observed photometry. The data span 2.0 to 35.0  $\mu\text{m}$ , tabulated at 0.1  $\mu\text{m}$  intervals from 2.0 to 7.6  $\mu\text{m}$ , 0.5  $\mu\text{m}$  intervals from 23 to 35  $\mu\text{m}$ , and at the original, non-uniform LRS wavelengths in the region between 7.6  $\mu\text{m}$  and 23  $\mu\text{m}$ . The spectral irradiance uncertainty of the mean spectrum (column 3) is to be applied to the upper and lower envelop spectra as well. The data in a typical spectrum is plotted in Figure 4.



**Figure 4. Spectrum (23278+6000.AFBSA2 ) of an Oxygen-rich AGB Star Plotted as  $\lambda F_{\lambda}$  Versus  $\lambda$ . The datapoints plotted are the photometric observations with error bars. The solid line is the mean spectrum, while the dashed lines are the photometric upper and lower bound spectra.**

**NOTE ADDED IN PROOF:**

Developments that occurred during the final production run of the Atlas dictated a more extensive use of the SWS spectra. The DUSTY models were found lacking as we applied them, and we reverted to our original concept of making maximum use of observed spectra. These changes are documented in a revised *Explanatory Supplement to the AFBSA V2* included in the Documentation Directory of the AFBSA V2 CD data disk.

## REFERENCES

- Beichman, C. A.; Neugebauer, G.; Habing, H. J.; Clegg, P. E.; Chester, Thomas J., 1988, Infrared astronomical satellite (IRAS) catalogs and atlases. Volume 1: Explanatory supplement
- Cohen, M., Walker, R.G., Barlow, M.J., and Deacon, J.R., 1992, Spectral Irradiance Calibration in the Infrared, I. Groundbased and IRAS Broadband Calibrations, *Astron. J.* Vol **104**, No.4, 1650-1657.
- Cohen, M., Walker, R.G. and Witteborn, F., 1992, Spectral Irradiance Calibration in the Infrared, II. Alpha Tau and the Recalibration of the IRAS Low Resolution Spectrometer, *Astron. J.* Vol **104**, No.5, 2030-2044.
- Cohen, M., Witteborn, F.C., Carbon, D.F., Augason, G.C., Wooden, D., Bregman, J.D., & Goorvitch, D. 1992, Spectral Irradiance Calibration in the Infrared, III. The Influence of CO and SiO, *Astron. J.*, v**104**, 2045
- Cohen, M., Witteborn, F.C., Walker, R.G., Bregman, J.D., and Woden, D.H., 1995, Spectral Irradiance Calibration in the Infrared, IV. 1.2-35 Micron Spectra of Six Standard Stars, *Astron. J.*, vol. **110**, no. 1
- Cohen, M. & Davies, J.K. 1995, Spectral Irradiance Calibration in the Infrared, V. The Role of the UKIRT and the CGS3 Spectrometer, *Mon. Not. Roy. Astron. Soc.*, v**275**, p715
- Cohen, M., Witteborn, F.C., Bregman, J.D., Wooden, D.H., Salama, A., & Metcalfe, L. 1996, Spectral Irradiance Calibration in the Infrared, VI. Three Southern Standards, *Astron. J.*, v**112**, p241
- Cohen, M., Witteborn, F.C., Carbon, D.F., Davies, J.K., Wooden, D.H., & Bregman, J.D. 1996, Spectral Irradiance Calibration in the Infrared, VII. New Composite Spectra, Comparisons with Model Atmospheres, and Far-IR Extrapolations, *Astron. J.*, v**112**, p2274
- Cohen, M., Witteborn, F.C., Roush, T., Bregman, J.D. & Wooden, D.H. 1998, Spectral Irradiance Calibration in the Infrared, VIII. 5-14 Micron Spectroscopy of the Asteroids Ceres, Vesta, and Pallas, *Astron. J.*, v**115**, p1671
- Cohen, M., 1998, Spectral Irradiance Calibration in the Infrared, IX., Calibrated Stellar Spectra Using DIRBE Radiometry, *Astron. J.*, v**115**, p2092
- Cohen, M., Walker, R.G., Carter, B., Hammersley, P., Kidger, M. and Noguchi, K., 1999, Spectral Irradiance Calibration in the Infrared. X. A Self-Consistent Radiometric All-Sky Network of Absolutely Calibrated Stellar Spectra, *Astron. J.*, **117**, 1864-1889
- M. Cohen, 1993, A Model for the 2-35 micron Point Source Infrared Sky, *Astron. J.*, **105**, 1860

Egan, M.P., Price, S.D., Moshir, M.M., Cohen, M., Tedesco, E., Murdock, T.L., Zweil, A., Burdick, S., Bonito, N., Gugliotti, G.M. and Duszak, J., *The Midcourse Space Experiment Point source Catalog Version 1.2 Explanatory Guide*. AFRL-VS-TR-10999-1522, ADA 381 933 (1999).

Gezari D.Y., Pitts P.S., and Schmitz M., 1999, Catalog of Infrared Observations, Edition 5, Unpublished

Hanner, M. S., 1988, NASA Conference Publication 3004, p22

Ivezic, v Z. & Elitzur, M. 1997, Self-similarity and Scaling Behavior of Infrared Emission from Radiatively Heated Dust, I. Theory, *Mon. Not. Royal Astron. Soc.* **287**, 799; Erratum:1999, *Mon. Not. Royal Astron. Soc.* **303**, 864

Jura, M. 1994, The Particle-Size Distribution In The Dust Ejected From IRC +10216, *Astrophys. J.*, **434**, 713

Kim S.H., Martin P.G. & Hendry P.D. 1994, The Size Distribution Of Interstellar Dust Particles As Determined From Extinction, *Astrophys. J.*, **422**,164

Mathis J.S., Rumpl W. & Nordsieck K.H. 1977, The Size Distribution Of Interstellar Grains, *Astrophys. J.*, **217**, 425

Ossenkopf, V., Henning, Th. & Mathis, J.S. 1992, Constraints On Cosmic Silicates, *Astronomy & Astrophysics*, **261**, 56

Pegourie, B., 1988, Optical properties of alpha silicon carbide, *Astronomy and Astrophysics*, vol. 194, no. 1-2, p. 335-339

Smith, B, J., 2003, Infrared Colors and Variability of Evolved Stars from COBE DIRBE Data, *Astronomical Journal*, Volume 126, Issue 2, pp. 935-963.

Walker, H. J., & Cohen, M., 1988, The Classification of Stars From IRAS Colors, *Astron. J.*, **95**, 1801.